

# Pressurized Gas Hadron Monitor for Intense Neutrino Beam Facilities

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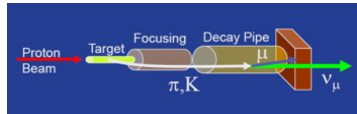
## Abstract

*The Long Baseline Neutrino Facility (LBNF), once achieving the design primary proton beam power of 2 MW and beam energy between 60-120 GeV, will produce the highest-intensity neutrino beam at Fermilab. This beam will be utilized in neutrino studies research in the Deep Underground Neutrino Experiment (DUNE). The beamline will bridge a distance of 800 miles between the near detector at Fermilab in Batavia, IL, and the far detector at Sanford Underground Research Facility in Lead, SD. Without a means of aligning the beamline of weakly-interacting neutrinos between detectors, the accuracy of the transverse alignment of the primary proton beam is critical. A small displacement in beam angle will result in a significant beam offset at the far detector. Current hadron monitor designs for Fermilab's high-intensity neutrino beam facilities are not fit to withstand the high-radiation environments created by MW-scale beam production targets. A gas-filled RF resonator hadron monitor is proposed to observe this alignment downstream of the target and preceding the beam absorber and near detector system.*

*A preliminary horn electric field map was input to G4Beamline, a particle tracking simulation program, which the position, momentum, global time, and PDGid (Particle Data Group identification) number parameters for each track. Simulation output data was used to construct a universal MATLAB R2014a script to assign particle classification-dependent mass energies to each track; map position-dependent electric field within resonator strips; and determine total RF power dissipation within the resonator.*

## I. INTRODUCTION

At the Long Baseline Neutrino Facility (LBNF) at Fermilab, the Main Injector will send a 60-120 GeV proton beam through a carbon graphite target, producing a beam of secondary charged particles. The secondary charged particle beam will include pions, which will decay into muons, which will in turn decay to muon neutrinos (Figure 1).



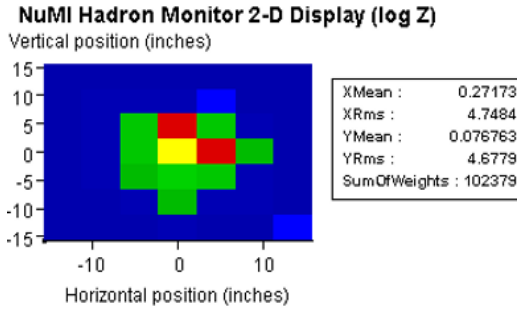
**Figure 1:** Neutrino beamline production from the decay of secondary particles produced from the interaction of a proton beamline with a carbon graphite target[1]

In order for the muon neutrinos, travelling at the speed of light, to have enough time to oscillate, they will be directed to a far detector 800 miles away at the Sanford Underground Research Facility. The vast distance over which the neutrinos must travel necessitates accurate alignment between the near and far detectors. Since neutrinos are only affected by the weak atomic force and gravity, no electromagnetic focusing elements can be implemented to direct their path. Furthermore, the only means of observing the neutrino beamline alignment is through observation of the trajectory of the secondary charged particle efflux, the neutrino progenitor. A hadron monitor is used to detect the transverse position of this secondary particle beam.

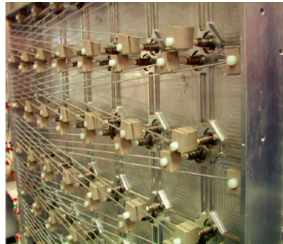
## II. METHODS

### Technology

The Neutrinos at the Main Injector, or NuMI, facility is Fermilab's current long-baseline (spanning 450 miles) neutrino facility. The hadron monitor employed at NuMI comprises a 7x7 array of ionization chambers covering a surface area of 1 m<sup>2</sup> [2]. Signal readout provides an analogous 7x7 pixelated beam profile, with each ionization chamber indicating a charge readout for the beam in both horizontal and vertical views. The juxtaposition of these views gives the spatial profile (Figure 2). Each ionization chamber is connected to two cables: a high voltage supply cable and a signal readout cable (Figure 3).



**Figure 2:** NuMI horizontal and vertical beam position display [2]

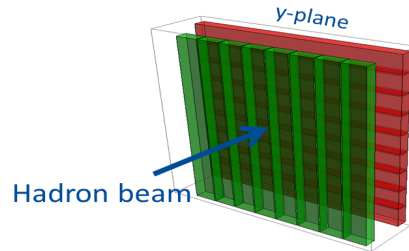


**Figure 3:** NuMI custom high voltage and signal readout cabling [2]

The major challenge this design poses is that the cabling, which lies in the beam path, is susceptible to radiation damage and signal pickup. As future hadron monitors—including the LBNF monitor—operate in increasingly high radiation environments, a next-generation design is proposed to improve the monitor sensitivity to radiation.

### Proposed Design

A gas-filled RF resonator is proposed to monitor the beam spatial distribution in intense radiation environments. The resonator is divided into seven strips. As charged particles pass through any one of the strips, they ionize the Nitrogen gas within, producing electron-ion pairs. The radiation sensitivity within each strip is regulated through individual adjustment of gas pressure and RF amplitude[3]. The front face of the monitor incorporates vertically-oriented plates, so that each plate will provide a horizontal coordinate for penetrating particles. To obtain a relative vertical coordinate for each particle, the plates comprising the back face of the monitor are horizontally-oriented (Figure 4).



**Figure 4:** RF resonator hadron monitor proposed for LBNF [3]

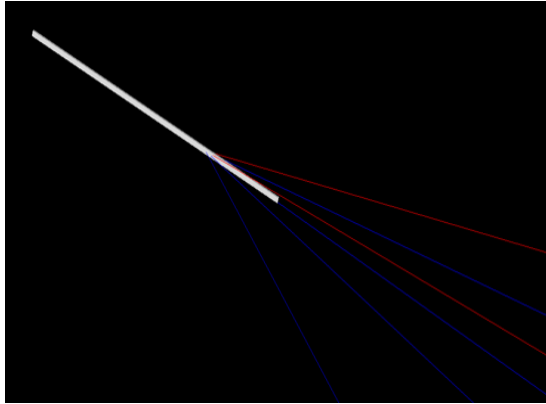
### Simulation

To begin modeling the environment in which the hadron monitor will operate, G4Beamline was used to construct the incident beam. G4Beamline is a beamline simulation software based on the Geant4 toolkit and developed by Muons, Inc. G4Beamline input specifications are given in Table 1. G4Beamline also required a horn electric field map for the simulation, but since the LBNF horn has not been built, a placeholder field map was employed instead. The G4Beamline output provided  $x$ ,  $y$ , and  $z$  (mm) positions;  $P_x$ ,  $P_y$ , and  $P_z$  ( $\frac{GeV}{c}$ ) momenta; the global time,  $t$  (ns); and the Particle Data Group identification number (PDGid) for each tracked particle. In addition to particle tracking calculations, G4Beamline also provides a

visualization of the beamline based on particle charge (Figure 5).

**Table 1:** *G4Beamline Input Specifications*

Element	Parameter	Input
Beamline	Beam Profile	Gaussian
	Number of Proton Events	10,000
	$(\sigma_x, \sigma_y)$	(0.2, 0.2)
	Particles Tracked	protons, $\pi^+$ , $\pi^-$ , $K^+$ , $K^-$ , $\mu^+$ , $\mu^-$
	Mean Momentum ( $\frac{GeV}{c}$ )	120
Target	Dimensions (mm)	Height = 15 Width = 6.4 Length = 999.9
	Material	Carbon
Detector	Distance From Target (m)	100



**Figure 5:** *G4Beamline* allows for visualization of the primary beam - target - secondary beam simulation. Red lines track negatively-charged particles and blue lines track positively-charged particles.

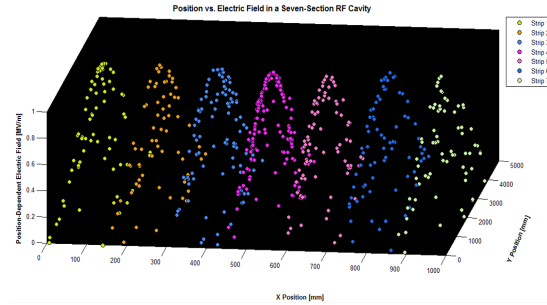
### III. RESULTS

A universal *MATLAB R2014a* script was developed to extract the data from a *G4Beamline* simulation of any parameterization and assign particle classification-dependent mass energies to each track; map position-dependent electric field; and to determine RF power dissipation within the resonator. The coordinates for each

particle were reconstructed according to which resonator strip the particles hit. The coordinates were re-initialized to local coordinates (coordinates defined relative to the strip's local origin as opposed to the hadron monitor's global origin), and these spatial coordinates were used to determine the sinusoidal component of the electric field experienced by each particle within the resonator (Equation 1). The amplitude of this field ( $E_0$ ) was input as unit size, and will ultimately depend upon the resonant frequency of the resonator.

$$E = E_0 \sin \frac{\pi x}{x_{max}} \sin \frac{\pi y}{y_{max}} \quad (1)$$

The electric field calculation was used to map the position-dependent electric field within the resonator (Figure 6).



**Figure 6:** *Reconstructed Position-Electric Field Hodoscopes*

Each track was assigned a new mass energy based on the PDGid number output from the script (Table 2).

**Table 2:** *PDGid and Mass Energy Assignments*

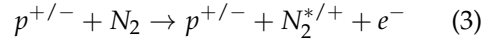
Particle Type	PDGid Number	Mass Energy ( $\frac{MeV}{c^2}$ )
proton	2212	938.272046
$\pi^+/-$	211	139.57018
$K^+/-$	321	493.667
$\mu^+/-$	13	105.6583715

The electric field,  $E$ , for each particle from the electric field mapping was input to the Bethe-Bloch equation (Equation 2). The mass

energy and the longitudinal momentum ( $P_z$ ) extracted from the G4Beamline output were used to calculate the relativistic  $\beta$  and  $\gamma$  for each particle. The constants  $K$ ,  $z$ ,  $Z$ ,  $A$ , and  $I$  are dependent upon the "stopping" (ionized) material (Nitrogen gas).

$$\frac{-dE}{dx} = \frac{Kz^2Z}{\beta^2} \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 E(\beta, \gamma)}{I^2} \quad (2)$$

As an incident charged particle,  $p^{+/-}$ , penetrates the gas-filled monitor, the Nitrogen within the monitor is either excited or ionized (Equation 3)[3].

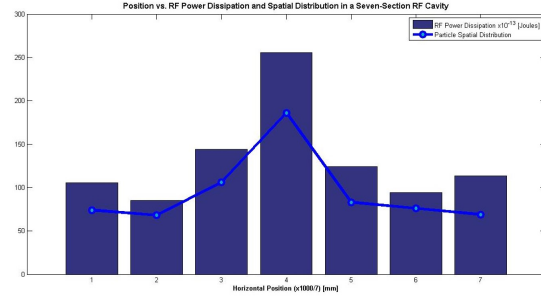


The number of electron-ion pairs produced from this ionization is required to determine power dissipation within the resonator. Knowing the number of incident particles,  $N_b$ ; the path length of the particles in the resonator,  $h$ ; and  $w_k$ ,  $\rho_m$ ,  $\frac{dE}{dx}$ , and  $W_i$ , (the statistical weight, density, stopping power, and ion pair production energy of Nitrogen gas, respectively), the number of electron-ion pairs,  $n_e$ , produced in the ionization of Nitrogen is determined by Equation 4 .

$$n_e = N_b \times h \sum_k w_k \left( \frac{\rho_m \frac{dE}{dx}}{w_i} \right)_k \quad (4)$$

Finally, the number of electron-ion pairs produced can be integrated over the power dissipation by a single electron ( $dw$ ) to give the total power dissipation within the resonator (Equation 5).

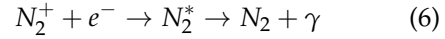
$$U = \int n_e dw \quad (5)$$



**Figure 7:** Total RF power dissipation integrated over each resonator strip volume and position-dependent particle spatial distribution

## IV. CONCLUSIONS

The goals of creating a feasible beamline simulation in G4Beamline, reconstruction of particle spatial distribution for ease of calculating electric field, and determining RF power dissipation within each resonator strip were achieved; however, many unknowns remain. In further investigations, the electron-ion recombination (Equation 6) rate will be considered as a time structure is developed for the monitor.



Temperature growth within the monitor as a result of free electrons gaining energy from the applied electric field will need to be determined. This growth in temperature and consequent heat deposition within the monitor may affect performance over time.

## V. ACKNOWLEDGMENTS

Many thanks to the adviser of this project, Katsuya Yonehara, who served as a direct conduit to answers to questions and resources in guidance of the investigation. Thanks also to Eric Prebys and Linda Spentzouris for all of the work they do to continue to strengthen the Lee Teng Undergraduate Fellowship program. The success of the Lee Teng program and of this project would not be possible without the organizational prowess of Tanja Waltrip, whose expert backstage handling of all intern programs and their components highly commendable.

## REFERENCES

- [1] Fermilab, *Highest-Intensity Neutrino Beam on the Planet*.
- [2] R. M. Z. et al., *Operation of the NuMI Beam Monitoring System*. Fermilab-Conf-06-090-AD.
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